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Sustainability and future alternatives of biogas-linked agrosystem (BLAS) in China: An emergy synthesis

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ABSTRACT

The biogas-linked agriculture has experienced a rapid development in recent years in rural China, which serves both as part of the country's developmental strategies of cleaner energy and an important reaction to sustainable agriculture call. This paper provides an overview of the economic and environmental performance of biogas-linked agrosystem (BLAS) in China by focusing on efficiency, emission mitigation effect and sustainability. An emergy synthesis combing emergy accounting and emergetic ternary diagram are utilized to evaluate the overall BLAS and its four subsystems (i.e., planting subsystem, breeding subsystem, aquaculture subsystem and biogas subsystem) in terms of current status and future development. Our findings indicate that despite a high energy transformity at system scale and a great dependence on economic input, BLAS advantages itself with high biogas production efficiency and significant emission mitigation effect. Furthermore, the sustainability zone analysis shows that the overall BLAS, planting and aquaculture subsystems maintain medium-term sustainability under all policy scenarios, despite the fact that breeding and biogas subsystems stay in an unsustainable situation due to their relatively severe environmental load. Among all the studied future options, continual biogas construction and effective technological revolution instead of expanding investment in traditional agriculture are preferable routes to further improve the system performance. Last but not least, emissions mitigation, energy efficiency and system sustainability are unveiled to be positively correlated within BLAS, which entitles it a promising energy alternative to enhance biogas energy utilization in the local agriculture in face of today's energy crisis.

Contents

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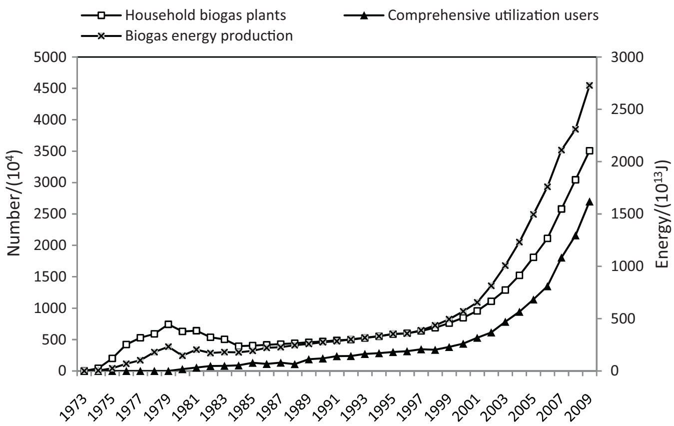


Fig. 1. Historical development of household biogas production in China (after [3,6]).

1. Introduction

The utilization of renewable energy resources has become a global strategy of sustainable energy use [1]. This is of particular importance for coping with the increasing stress from energy crisis and global warming. In this context, biogas construction rose as a key program of renewable energy construction worldwide, especially in rural areas where other renewable energy resources are scarce or unreachable [2–5].

China has a relatively long history of biogas exploration, but the systematical utilization was not formed until the 1920s when the first hydraulic digester was invented by Luo GuoRui in Taiwan, China. Despite a short decline from 1980 to 1985, household biogas construction and energy production have experienced a progressive development in rural China since the 1970s, which has been most noticeable since the beginning of the new century (Fig. 1). Up to 2009, some 35.07 million was put into use, which constituted 87% of the world's total number. This gave a direct boost to biogas energy production and the total energy produced by the household biogas plants was 2.73E+16 J in 2009. Meanwhile, the number of comprehensive biogas utilization users has also rapidly mounted into 27 million since the early 1980s. The development and implementation of biogas systems are being stimulated by the Chinese government in the existing incentives as well as the forthcoming policy stated in the government's 2011–2015 five-year plan, which is proposed in response to the rural economic development, energy structure adjustment and the overall carbon emission reduction target of 40–50% cut per unit of GDP before 2020.

As a major fashion of household biogas utilization in China, the development of biogas-linked agrosystem has become an important route to promote agricultural structure adjustment and enhance the renewable energy utilization in rural areas, which is closely embedded in the country's long-term framework of renewable energy development. Through years of practice, several typical modes of comprehensive biogas utilization including "Three in One", "Four in One" and "Five in One" eco-agriculture modes prevail over the country, linking biogas production to the agricultural industry chain. In face of the continuous constructions and applications of biogas systems to form so-called "eco-agriculture", it is crucial to probe into the sustainability and efficiency during energy production and comprehensive utilization process. In fact, the incorporation of anaerobic digestions into the complex agrosystem displays the advantages over the traditional agricultural practices and waste handling procedures in at least two ways: on one hand, it is a comparatively clean high methane fuel for electricity or heating; on the other hand, it is effective in the collection of organic waste material from which both fertilizer and slurry for agriculture use can be produced [7–9]. This is also how the concept "renewable" in terms of biogas utilization can be updated: not only should the lower emissions directly due to a cleaner fuel be emphasized, but also the indirect emission and pollution reduction benefit from the highly circulating material and energy flows in a closed input–output system. In view of these, we believe that it is essential to develop multi-angle methods with a fair consideration of the economic and environment aspects during system operating as well as at planning stage, preferably decision-making friendly ones.

Analytical measures of renewable energy efficiency and system sustainability mainly fall into three streams, i.e., benefit–cost economic analysis [2,10], environmental evaluation [7,8,11] and biophysical metrics [12,13]. However, consensus has not been reached yet regarding a generally accepted way to describe and determine sustainability, for each method mentioned above offers a specific insight into "upstream" or "downstream" impacts of a product or industry [14]. A detailed discussion can be referred to [15,16]. Emergy synthesis is recognized as a valid approach to assessing both environmental and economical costs of progress towards sustainability [15,17–20]. Compared to the other methods mentioned above, emergy synthesis proves to be a suitable tool to address the aggregated agricultural systems due to its strengths in analyzing the compound ecosystems at the interface between natural and human systems [21–25]. Within a unified emergy evaluation framework, both direct and indirect information of the system operation can be extracted and exposed by tracing back the ecological-economic processes [26,27]. Therefore, it is not inconceivable that emergy theory can provide valuable information for better understanding the sustainable level of a biogas system in the biophysical context. A few studies have been conducted so far to assess the biogas system via the emergy approach. Wei et al. [28] compared the efficiency and sustainability between a conventional peach production system and a 'Four in One' biogas-peach production system in the solar greenhouse based on the accounting of all emergy inputs and outputs of these two systems. Zhou et al. [29] analyzed the operation of a farm biogas project in China by using emergy analysis and explored its reliance on the local resources input, environmental pressure and sustainability, in which the economic benefits (market value) and ecological economic benefits (emergy monetary value) of the project were also discussed. Ciotola et al. [30] evaluated a small-scale biogas production and electricity generation system in Costa Rica with foci on emergy indices such as the proportion of renewable sources, systemic transformities and emergy sustainability. In quest of the sustainable management of biogas systems on a regulatory basis, there are still problems that needed to be addressed: first, it is not clear that if the biogas system still stands out as an efficient and sustainable energy system when it is generalized to the regional level; second, there is little information as to the sustainability of agricultural subsystems with the introduction of digesters, which is critical when considered the broader application of biogas systems; third, even though certain relationships between some important traits of biogas systems (e.g., transformity and emergy sustainability) have been observed [30], the tradeoff of building a energy system between emissions mitigation, efficient energy utilization and sustainable system has never been clarified in sufficient details. Meanwhile, an emergy-based ternary analytic tool termed as emergetic ternary diagram (EmTD) has been recently proposed to visualize the emergy evaluation results in an equilateral triangle to track the variations of system performance [31,32]. With the help of EmTD, it is capable to parse into the relationships and interaction between subsystems, which otherwise would be hidden in conventional emergy synthesis. Hence, the combination of emergy synthesis and emergetic ternary tool can hopefully realize a transparent interpretation of system performance and serve

as an effective interface between emergy scientists and decision makers.

In this study, we provide a concise overview of the current status of a complex biogas-linked agrosystem (consisting of subsystems such as planting, breeding, aquaculture and biogas) on regional scale through an emergy synthesis combing emergy accounting and emergetic ternary diagram, and explore future options for the system development by focusing on emissions mitigation, biogas energy efficiency and system sustainability. The rest of this paper is organized as follows. In Section 2, two major methods employed, emergy accounting and emergetic ternary diagrams are introduced, and the case study in Gongcheng County (China) and the future developmental scenarios are described, and in Section 3, system performance of BLAS and its subsystems is addressed based on emergy evaluation results and emergetic ternary diagrams, and then, major findings derived from the results are discussed in Section 4. Finally, some concluding points of this study are provided in Section 5.

2. Materials and methods

2.1. Biogas-linked agrosystem (BLAS)

The system under consideration is the biogas energy and biomass linked complex agrosystem in Gongcheng Yao Autonomous County for the year 2009, which we call a biogas-linked agrosystem (BLAS). It is located in the minority mountain area of South China, where the Yao people have very limited sources of income by engaging in traditional agricultural activities such as cropping and tea planting. But since 1970s, the local economy of the county has gone through a rapid development due to progressive household biogas construction, which not only raises the daily incomes of the local people but also profoundly influence their ways of living. Up to 2009, 63.6 thousand household biogas digesters have been put into use and the current biogas users account for 89% of all families, serving as one of the most bioenergy-intensive areas in China.

Over the same period, the BLAS pattern was formed by the World Bank Project of Rural Eco-homes[1] and has become the major fashion of local agricultural production[2]. Despite the differences in the concrete modes of biogas comprehensive utilization, the BLAS comprises four subsystems basically: planting subsystem, breeding subsystem, aquaculture subsystem and biogas subsystem. The joint benefits of these subsystems are huge: the conventional commercial energy that was reduced by biogas production in 2009 equaled 129.2 kilotons of standard coal; also greenhouse gas emissions were mitigated so that 48 700 ha of forest area was free from destruction. Meanwhile, 17 120 kilotons of biogas slurries and residues provided by the digesters supplied other subsystems (planting breeding and aquaculture) perfectly as organic and low-pollution fertilizers, pesticides, or feeds and the incomes of farmers were raised by 1.27 billion in total compared to the year 2008. The average income of the Yao people was raised to 4188 RMB per capita in 2009, approximately 5 times as that before biogas construction.

[1] Initiated by the Chinese Government and the World Bank, the World Bank Project of Rural Eco-homes concerns the comprehensive utilization of rural household biogas in Anhui, Chongqing, Hubei, Hunan and Guangxi provinces of China. Through the construction of rural household biogas plants, as well as the associated transformation of kitchens, toilets and pigpens, the project encourages farmers to use methane via a new eco-agricultural technique.

[2] BLAS of Gongcheng county has been entitled as National Sustainable Development Experimental Zone and the United Nations Model of Ecological-economic Rural Development Zone in Developing Countries.

2.2. Emergy synthesis (EmS)

H.T. Odum pioneered the development of emergy in the 1970s and defined it as the sum of the available energy of one kind previously required directly and indirectly through input pathways to make a product or service [33]. Now it has been widely accepted as an effective energy accounting framework. Interestingly enough, emergy per se is a teleological explanation of the universe [34], representing “the energy memory” or the total historical energy embodied in any substances. From emergists’ points of view, the social sustainable development, if possible, should be founded on the thermodynamic laws that govern both natural and cosmic evolution processes and thus make bridges between human production, economic production, and environmental production [35,36].

As for emergy synthesis, all the inputs along the forming process are converted into solar emergy (sej) by multiplying the inputs with their respective conversion factors in terms of solar transformity (sej/J). Fundamentally, emergy synthesis provides an eco-centric view of the operating world from the environmental aspect rather than according to the value to humanity stated in the view of modern economics [18]. However, it still plays a role as a complementary method for its unique strength in determining the conditions of ecological systems based on the unified value of environmental and economic work [16], therefore capable of representing BLAS in both environmental and economic values when we are assessing the long-term sustainability and eco-efficiency of various ecosystems. In the emergy accounting, Odum (1996) [37] was used as the baseline, while the transformities prior to the year 2000 are updated values multiplied by 1.68 (which is consistent with the baseline used in [28,29], whereas different from that of [30]).

Fig. 1 shows the aggregated system emergy flows of a typical BLAS. The emergy inputs are parsed into three categories [31]: renewable resources (R), non-renewable resources (N) and the economic inputs (F). The R and N flows are economically free input offered by the local environment, of which the renewable resources can be replaced at least at the same rate as they are consumed, while the non-renewable resources are depleted faster than their ability of recuperation. The F flows are provided by the market and are accounted by the economy. The emergy yield (Y) represents the output of total emergy produced or released by the concerned system.

Emergy-based indicators offer effective sustainability metrics to evaluate the utilization of bioenergy and biomass and track the ecological and economic behaviors of BLAS. Below are the five basic emergy-based indices established for the evaluation of BLAS with respect to system efficiency, yield, environmental load and sustainability level. More details of the significations of these indices can be found in [17,38].

2.3. Emergetic ternary diagram (EmTD)

Emergetic ternary diagram (EmTD) is an integrated tool that combines emergy accounting with ternary diagram [31,32]. Different from other emergy representation forms (e.g., [40,41]), EmTD functions as a diagram of exhibiting emergy evaluation results and a data treatment platform. The special data disposal and graphic representation provided by EmTD make it possible to compare various processes and systems, evaluate improvements and follow the system performance over time. With the aid of ternary diagrams, aspects such as the interactions between systems and the interactions between systems and the environment can be recognized and evaluated.

EmTD parses the system based on three basic emergy input categories (i.e., R, N, F) in accordance with the emergy synthesis

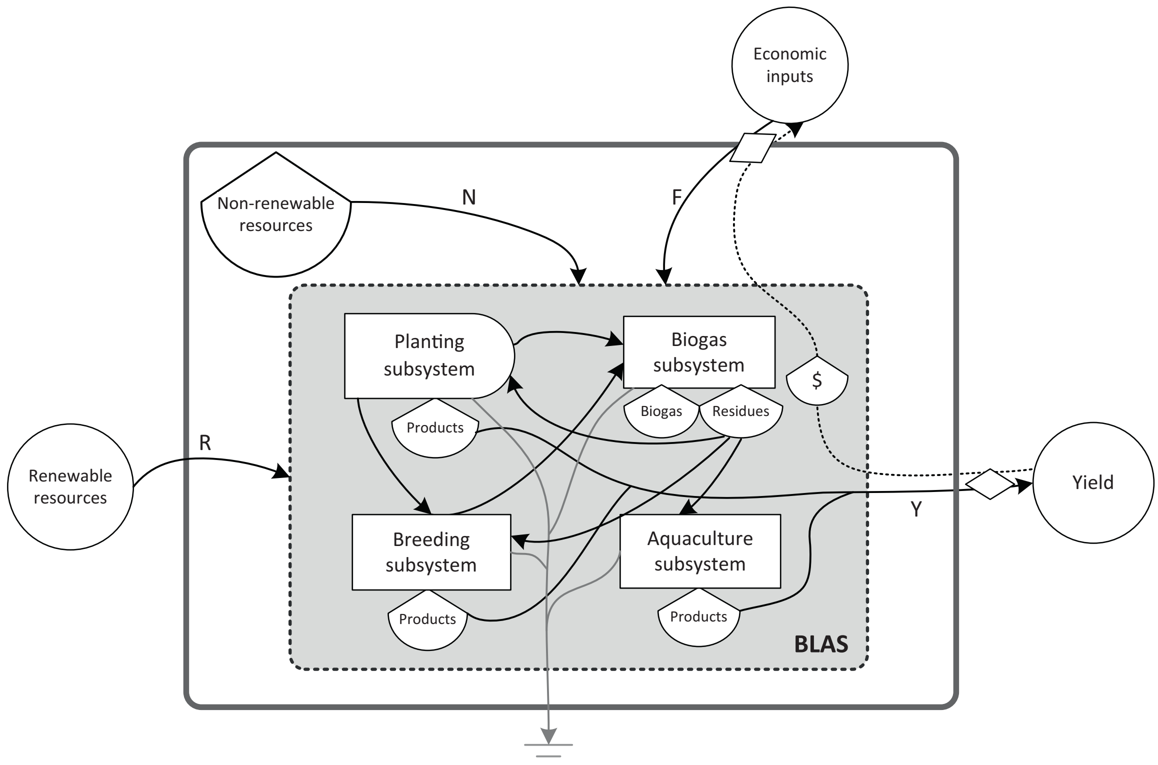


Fig. 2. Aggregated energy flow diagram for BLAS. R: Renewable resources; N: non-renewable resources; F: economic inputs; Y: yield.

mentioned above (Fig. 2). Each category is represented as an element (apex) in an equilateral triangle, with the relative proportions of each element being given by the lengths of the perpendicular from the given point to the side opposite to the corresponding element of the triangle. In such a way as defined, ternary combinations that reflect the changes of the concerned emergy system are represented by points within the triangle. Due to the formulation of the basic indices based on R, N and F, it can visually represent some of the emergy indices (i.e., ELR, EYR, EIR, SI) that can assist the comparison of different development paths or strategies, which is critical for tracking the sustainability scenario of BLAS.

In fact, besides the regular graphic representation, EmTD betters itself in the release or identification of some component-specific traits and system evolution trends, therefore investigating the system performance in a more explicit way compared to the traditional interpretations. Regarding these, we concluded in four aspects as follows:

- System aggregation analysis (Fig. 3a): EmTD allows an aggregated analysis of various combinations of subsystems. When two different ternary compositions (subsystems), say point *p* and *q* within the triangle, are jointly considered, the combined system can be represented by a resultant point termed as simergic point (*S*) that lies somewhere between *p* and *q*.
- Input sensitivity analysis (Fig. 3b): A tracking of system's developmental trends is possible based on input sensitive lines. Any point along the straight line that joins an apex to a given point represents a change in the quantity of the flux associated to the apex. Other points along the line share the same initial proportion of other two fluxes. For example, the system illustrated below is progressively poorer in N, as it passes from p to q, leaving R and F at the same initial proportion.
- Resource equivalence analysis (Fig. 3c): The equivalence to a certain resource value (e.g., R) is represented by the relative resource line (R resource line) that is parallel to the triangle side opposite to the appropriate element within the diagram. It is very useful for comparing the use of resources by-products or processes. As the sum of R, N and F equals 100% by definition, three pertinent emergy-based indices can be further formulated as: EYR = 100/F, EIR = F/(100 − F) (shown with the F resource line); ELR = (100 − R)/R (shown with the R resource line).
- Sustainability zone analysis (Fig. 3d): EmTD provides an expedient way to indicate constant values of the sustainability index. In the ternary diagram, SI can be further formulated as: 100R/(100 − R)F. The corresponding sustainability lines turn out to be specific curves that depart from the N apex in the direction of the RF side, allowing divisions of the triangle into distinct sustainability zones (e.g., points *p* and *q* are in different sustainability zones that are separated by a sustainability line, mostly according to the criteria depicted in Table 1), which are indicative when we are identifying and comparing the sustainability of different systems and processes.

2.4. Description of future scenarios

The development of BLAS is being stimulated by both existing and forthcoming governmental incentives. In order to explore the future development direction and sustainability of BLAS, three specific scenarios for 2015 are hypothetically designed based on an explicit policy investigation of biogas energy and eco-agricultural development at local as well as country scale, while another two scenarios are set by a combination of the former ones. These scenarios are mainly focused on such aspects as biogas construction, investment expanding and technical renovation, which all potentially contribute to the changes in emergy input, structure of BLAS and its subsystems. Descriptions of scenario settings and responsive changes with respect to system input are listed in Table 2 (the items of the responsive changes are within the emergy input list in Table 3).

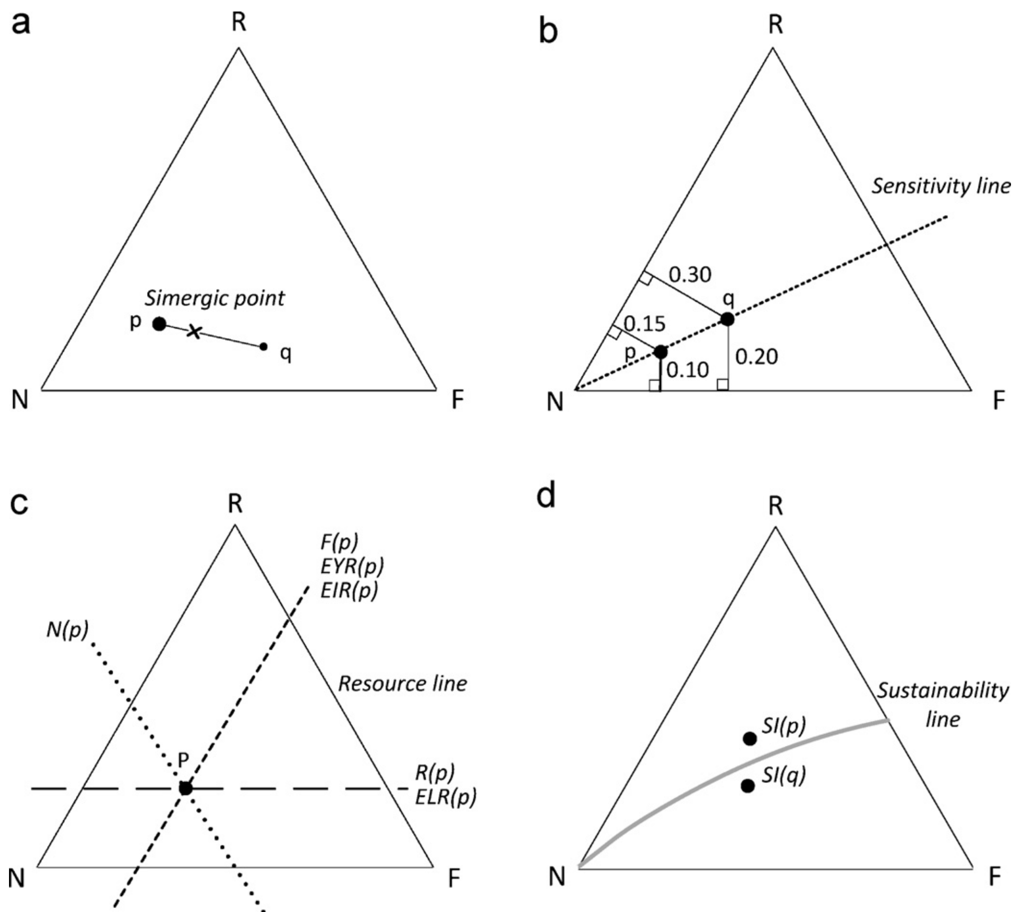


Fig. 3. Emergetic ternary diagrams for (a) system aggregation analysis, (b) input sensitivity analysis, (c) resource equivalence analysis and (d) sustainability zone analysis. R: Renewable resources; N: non-renewable resources; F: economic inputs; SI: sustainability index; EYR: environmental yield ratio; EIR: environmental investment ratio; ELR: environmental loading ratio (after [32]).

3. Results

3.1. Emergy synthesis of BLAS

3.1.1. Emergy accounting

Emergy flows of overall biogas-linked agrosystem are summed up in Table 3, where the detailed categories of emergy input (including renewable resources (R), non-renewable resources (N) and economic input (F)) and emergy yield (Y) are calculated. The results show that the total emergy input of BLAS is 1.37E+21 sej (1.26E+21 sej without L&S). The energy of rain (chemical and geopotential) contributes most to the renewable energy of BLAS, while the labor and services (L&S), chemical fertilizers (nitrogen, phosphate, potash and compound fertilizer) serve as the two greatest emergy inputs, followed by Biosolid fertilizer and pig feed. Based on the emergy flow evaluation, indices such as empower density, unit empower, transformity and specific emergy are also evaluated to address energy flow intensity and system efficiency of BLAS. In addition, the aggregated emission mitigation magnitude of BLAS as opposed to traditional agricultural system is determined.

The components of BLAS including emergy input and yield of the four subsystems (i.e., planting, breeding, aquaculture and biogas subsystem) are also accounted and compared (Table 4). The result indicates planting subsystem is the biggest constituent of BLAS (U = 1.17E+21 sej), while the rest subsystems share an analogous scale with regard to the total emergy input. Similar

Table 1
Emergy-based indices for BLAS evaluation [37–39].

Symbol	Formulation	Implication
BEE	Y_b/F	i.e., Biogas energy efficiency, it is a metric of the production efficiency of biogas energy, calculating by the ratio of produced biogas (Y_b) to economic input (F).
EMI	EM/U	i.e., Emission mitigation intensity, it measures the net emission mitigation (EM) for per unit emergy input.
EYR	U/F = (F + R + N)/F	i.e., Environmental yield ratio, it is a measure of the ability of a process to exploit available locally renewable and non renewable resources by investing outsider sources. The higher the value of this index, the greater the return obtained per unit of emergy invested.
ELR	(N + F)/R	i.e., Environmental loading ratio, it is a measure of the possible disturbance to the local drive from outside sources. The lower the ratio is, the lower the stress is to the environment. When 3 < ELR < 10: the impact is considered moderate; ELR > 10: there is a high environmental loading; Extremely high values of ELR: the offer of local renewable inputs is not enough to supply the process demands.
SI	EYR/ELR	i.e., Sustainability index, it is an aggregating index based on both interaction with the surrounding environment and renewability. When SI < 1: products and processes are not sustainable in a long term; 1 < SI < 5: point E, may make a sustainable contribution to the economy for medium periods and processes; SI > 5: sustainable in a long term.

Table 2
Descriptions of five developmental scenarios of BLAS.

Scenario	Description
Scenario I (S1)	※ *Scenario setting* Another 6500 biogas digesters are built before 2015 (i.e., approximately 10% of the existing biogas digesters). ※ *Responsive changes* Soil loss (−20%), labor and management (−10%), biosolid fertilizer (−30%), electricity (−10%), biogas construction and maintenance (+10%), nitrogen (−20%), phosphate (−20%), potash (−20%), compound fertilizer (−20%), pesticide (+20%), infrastructures (+10%), ceteris paribus.
Scenario II (S2)	※ *Scenario setting* The investments in planting, breeding and aquaculture industry are all increased by 30% while the number of biogas digesters maintains status quo. ※ *Responsive changes* Soil loss (+30%), labor and management (+20%), seedlings (+30%), grains (+30%), biosolid fertilizer (+20%), electricity (+10%), diesels (+30%), machinery (+20%), pig feed (+30%), fish feed (+30%), plastic films (+20%), nitrogen (+20%), phosphate (+20%), potash (+20%), compound fertilizer (+20%), pesticide (+20%), infrastructures (+30%), ceteris paribus
Scenario III (S3)	※ *Scenario setting* Chemical fertilizer and pesticide inputs are cut by 30% with an enhancement of the comprehensive use of biogas slurry and residue, also the construction cost of biogas facilities are reduced by 40% due to technical renovation, while the number of biogas digesters maintains the status quo. ※ *Responsive changes* Labor and management (−20%), biosolid fertilizer (−30%), electricity (−10%), nitrogen (−30%), phosphate (−30%), potash (−30%), compound fertilizer (−30%), pesticide (−30%), infrastructures (−30%), ceteris paribus
Scenario IV (S12)	※ *Scenario setting* A combination of Scenario I and Scenario II.
Scenario V (S13)	※ *Scenario setting* A combination of Scenario I and Scenario III.

to total emergy input, the highest empower density and unit empower are both observed in planting subsystem. Aquaculture and biogas subsystem have the highest and lowest transformity, respectively, either with or without L&S. As to specific emergy, again aquaculture has the higher value over other three subsystems (1.58E+10 sej/g with L&S, 1.30E+10 sej/g without L&S). Finally, EM results show that the major contributions of system emission mitigation are from planting (EM = 7.93E+10 g) and breeding (EM = 2.79E+10 g).

3.1.2. Emergetic ternary diagrams

As demonstrated in Table 5, the overall BLAS is characterized by 43% renewable resources (R), 9% non-renewable resources (N) and 48% economic input (F). The ratios of emergy input categories (R, N, and F) within planting and breeding subsystem are similar to BLAS, while aquaculture and biogas subsystem distinguish themselves with heavier economic inputs, respectively. The emergy structures of these systems are illustrated more intuitively in Fig. 4 in the form of emergetic ternary diagrams (EmTD). For example, within

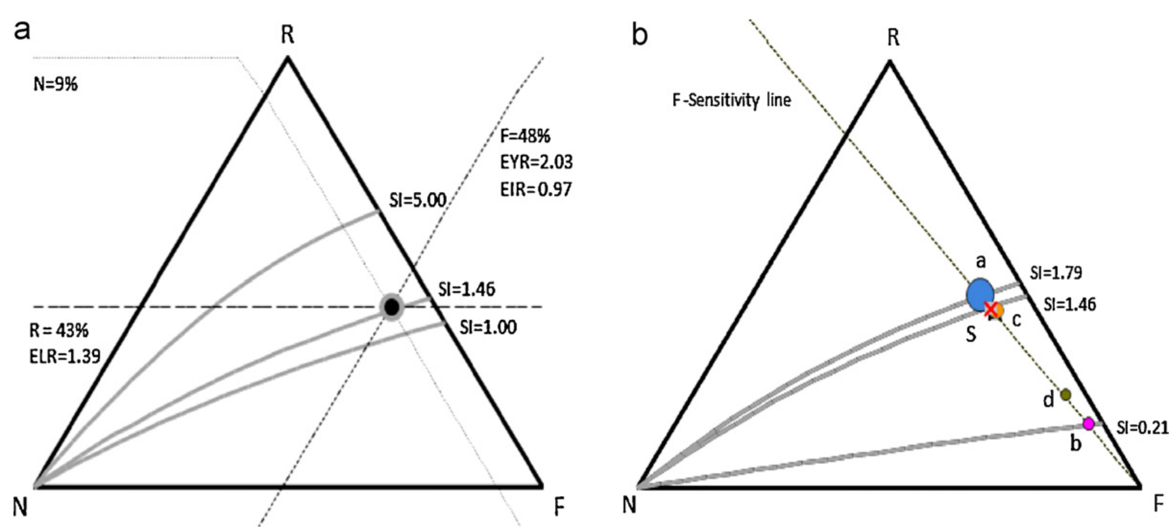


Fig. 4. Emergetic ternary diagrams for (a) BLAS and (b) its subsystems. Point a: Planting subsystem; Point b: Breeding subsystem; Point c: Aquaculture subsystem; Point d: Biogas subsystem; Point S: Simergic point of all subsystems (also the BLAS's point calculating the overall system). *F*-Sensitivity line is a straight line joining the F apex to Point a. R: Renewable resources; N: non-renewable resources; F: economic inputs; SI: sustainability index; EYR: environmental yield ratio; EIR: environmental investment ratio; ELR: environmental loading ratio.

Table 3
Emergy evaluation of overall BLAS (on per year basis).

Number	Item	Raw data	Unit	Transformity (sej/unit)	Reference. of transformity	Solar emergy (sej)
Renewable resources (R)						
1	Solar radiation[a]	9.90E+18	J	1.00E+00	By definition	9.90E+18
2	Rain, chemical[b]	1.53E+16	J	3.06E+04	[37]	4.68E+20
3	Rain, geopotential[c]	2.43E+16	J	1.49E+04	[37]	3.63E+20
4	Wind, kinetic[d]	1.49E+17	J	1.11E+03	[37]	1.66E+20
5	Earth cycle[e]	2.15E+15	J	4.87E+04	[37]	1.05E+20
Total						5.73E+20
Non-renewable resources (N)						
6	Soil loss[f]	9.65E+14	J	1.24E+05	[45]	1.20E+20
Total						1.20E+20
Economic inputs (F)						
7	Labor and services[g] (L&S)	1.79E+07	US $	5.87E+12	[20]	1.05E+20
8	Seedlings	1.97E+05	US $	5.87E+12	[20]	1.16E+18
9	Grains	5.66E+13	J	1.39E+05	[26]	7.89E+18
10	Biosolid fertilizer[h]	1.71E+13	J	4.54E+06	[37]	7.76E+19
11	Electricity	7.74E+12	J	3.36E+05	[37]	2.60E+18
12	Diesels	2.94E+13	J	1.11E+05	[37]	3.26E+18
13	Machinery	2.50E+09	g	1.12E+10	[37]	2.80E+19
14	Biogas construction and maintenance	7.80E+05	US $	5.87E+12	[20]	4.58E+18
15	Pig feed	7.12E+06	US $	5.87E+12	[20]	4.18E+19
16	Fish feed	4.05E+05	US $	5.87E+12	[20]	2.38E+18
17	Plastic films	5.88E+09	g	1.11E+05	[46]	6.53E+14
18	Nitrogen	2.55E+10	g	6.38E+09	[37]	1.63E+20
19	Phosphate	1.15E+10	g	6.55E+09	[37]	7.53E+19
20	Potash	9.03E+09	g	1.74E+09	[47]	1.57E+19
21	Compound fertilizer	1.80E+10	g	4.70E+09	[26]	8.47E+19
22	Pesticides	2.38E+09	g	2.52E+10	[45]	6.00E+19
23	Infrastructure	3.01E+05	US $	5.87E+12	[20]	1.77E+18
Total						6.74E+20
Yield (Y)						
24	Planting products	2.54E+15	J	8.30E+04	[26]	2.11E+20
25	Breeding products	5.38E+14	J	1.71E+06	[26]	9.20E+20
26	Aquaculture products	2.50E+13	J	2.00E+06	[26]	5.00E+19
27	Biogas	5.35E+14	J	2.48E+05	[21]	1.33E+20
Total						1.31E+21
EM[i]		1.21E+11	g			
Total input with L&S		1.37E+21	sej			
Total input without L&S		1.26E+21	sej			
Empower density[j]		6.37E+11	sej/m^2			
Unit empower[k]		5.78E+15	sej			
Transformity with L&S[l]		3.77E+05	sej/J			
Transformity without L&S		3.46E+05	sej/J			
Specific emergy with L&S[m]		1.53E+10	sej/g			
Specific emergy without L&S		1.40E+10	sej/g			

[a] Solar energy = (the average radiation of Guangxi Province) × (area) = (4.61E+9 J/m^2/yr) × (2.15E+9 m^2) = 9.90E+18 J/yr; average radiation in Guangxi Province is 4.61E+9 J/m^2/yr.
[b] Rain energy (chemical) = (area) × (average rainfall) × (density) × (Gibbs free energy) = (2.15E+9 m^2) × (1.44 m/yr) × (1.00E+6 g/m^3) × (4.94 J/g) = 1.53E+16 J/yr; average rainfall in Guangxi Province is 1.44 m/yr [42].
[c] Rain energy (geopotential) = (area) × (mean altitude) × (average rainfall) × (density) × (acceleration of gravity) = (2.15E+9 m^2) × (800 m) × (1.44 m/yr) × (1.00E+10^3 kg/m^3) × (9.8 m/s^2) = 2.43E+16 J/yr [42].
[d] Wind energy = (area) × (air density) × (eddy diffusivity) × (gradient velocity) = (2.15E+9 m^2) × (1.30 kg/m^3) × (1.80 m^2/s) (3.15E+7 s/yr) = 1.49E+17 J/yr.
[e] Energy of earth cycle = (area)(heat flux) = (2.15E+9 m^2)(1.00E+6 J/m^2/yr) = 2.15E+15 J/yr.
[f] Energy of soil loss = (area of agricultural land)(soil loss rate)(organic matter content) × (5.40E+6 kcal/t) × (4186 J/kcal) = (1.82E+8 m^2) × (6.5E−03 t/m^2/yr) × (0.036) × (5.40E+6 kcal/t) × (4186 J/kcal) = 1.41E+15 J/yr; soil loss rate of Guangxi Province is 6.5E−03 t/m^2/yr, and organic matter content is 0.036 [43].
[g] Labor and services = (area of agricultural land) × (average wage) × (the exchange rate between RMB and US$ in 2000) = (1.82E+8 m^2) × (0.79 RMB/m^2/yr) × (1/8.3) = 1.79E+7 US$/yr.
[h] The transformity of biosolid fertilizer (reused biogas slurry and residue) is chosen based on the work of Wei et al. [28], whose value is between 5.77E+06 [29] and 1.87E+05 [30].
[i] The determination of the emission mitigation of BLAS is based on the assumption that it equals the scaling up of the emission mitigation effect of a typical biogas plant used in Gongcheng County, i.e., 8 m^3 household biogas plant [44]. CO_2 and CH_4 emissions are considered here, i.e., EM = EM(CO_2) + EM(CH_4); EM(BLAS) = EM(CO_2) + EM(CH_4) = (1.41E+6 g + 4.93E+5 g) × 63 600 = 1.21E+11 g.
[j] Empower density = U/area.
[k] Unit empower = U/population; the population of BLAS in Gongcheng County is 237 000.
[l] Transformity = U/total energy of system yield.
[m] Specific emergy = U/total biomass of system yield.

the left EmTD, the point representing BLAS located closer to line RF compared to NR and NF, indicating the system is largely reliant on the renewable resources and economic input and with a low cost of non-renewable resources. The R resource line depicts the environmental loading ratio (ELR) of BLAS, N resource line is drawn to present non-renewable proportion, while F resource line shows BLAS's system situation indicated by ratios like environmental yield ratio (EYR) and environmental investment ratio (EIR). Sustainability zone analysis reveals the current BLAS is within 1–5 zone (SI = 1.46), and all the subsystems are below SI = 5 sustainability line, with planting as the most sustainable one (SI = 1.79) and breeding the least likely to be sustainable (SI = 0.21). In this evaluation, simergic point of these subsystems conceivably equals the overall BLAS. Through the straight line linked by F apex and b

Table 4
Emergy evaluation of BLAS's subsystems (on per year basis).

Number	Item	Solar emergy/(sej)			
		Planting	Breeding	Aquaculture	Biogas
Renewable resources (R)					
1	Solar radiation	9.10E+18	2.00E+17	4.34E+17	1.66E+17
2	Rain, chemical	4.30E+20	9.45E+18	2.05E+19	7.86E+18
3	Rain, geopotential	3.33E+20	7.33E+18	1.59E+19	6.10E+18
4	Wind, kinetic	1.53E+20	3.35E+18	7.27E+18	2.79E+18
5	Earth cycle	9.63E+19	2.12E+18	4.59E+18	1.76E+18
Total		5.26E+20	1.28E+19	2.78E+19	1.06E+19
Non-renewable resources (N)					
6	Soil loss	1.10E+20	2.42E+18	5.24E+18	2.01E+18
Total		1.10E+20	2.42E+18	5.24E+18	2.01E+18
Economic inputs (F)					
7	Labor and services(L&S)	5.28E+19	1.39E+19	1.51E+19	2.32E+19
8	Seedlings	1.16E+18	–	–	–
9	Grains	7.89E+18	–	–	–
10	biosolid fertilizer	5.82E+19	8.53E+18	1.09E+19	–
11	Electricity	7.80E+17	9.10E+17	6.50E+17	2.60E+17
12	Diesels	1.14E+18	8.15E+17	4.89E+17	8.15E+17
13	Machinery	1.26E+19	4.20E+18	4.20E+18	7.00E+18
14	Biogas construction and maintenance	–	–	–	4.58E+18
15	Pig feed	–	4.18E+19	–	–
16	Fish feed	–	–	2.38E+18	–
17	Plastic films	6.53E+14	–	–	–
18	Nitrogen	1.63E+20	–	–	–
19	Phosphate	7.53E+19	–	–	–
20	Potash	1.57E+19	–	–	–
21	Compound fertilizer	8.47E+19	–	–	–
22	Pesticides	6.00E+19	–	–	–
23	Infrastructure	8.83E+17	2.65E+17	1.77E+17	4.42E+17
Total		5.34E+20	7.05E+19	3.38E+19	3.63E+19
Yield (Y)					
24	Planting products	2.11E+20	–	–	–
25	Breeding products	–	9.20E+20	–	–
26	Aquaculture products	–	–	5.00E+19	–
27	Biogas	–	–	–	1.33E+20
Total		2.11E+20	9.20E+20	5.00E+19	1.33E+20
EM[a]		7.93E+10	2.79E+10	0	1.36E+7
Total input with L&S		1.17E+21	6.68E+19	8.57E+19	4.90E+19
Total input without L&S		1.12E+21	5.29E+19	7.06E+19	2.58E+19
Empower density		5.44E+11	3.11E+10	3.99E+10	2.28E+10
Unit empower		4.94E+15	2.82E+14	3.62E+14	2.07E+14
Transformity with L&S		4.61E+05	1.24E+05	3.43E+06	9.16E+04
Transformity without L&S		4.40E+05	9.83E+04	2.82E+06	4.82E+04
Specific emergy with L&S		1.35E+09	2.85E+09	1.58E+10	2.70E+09
Specific emergy without L&S		1.29E+09	2.26E+09	1.30E+10	1.42E+09

[a] EM (Planting) = (1.19E+6 g + 5.45E+4 g) × 63 600 = 7.93E+10 g; EM (Breeding) = (0 g + 4.38E+5 g) × 63 600 = 2.79E+10 g; EM (Biogas) = (2.15E+5 g + 0 g) × 63600 = 1.36E+10 g. The emission mitigation of aquaculture can be neglected in the current system.

(breeding), it is clear that other subsystems share the similar ratio of total R to N as the economic inputs vary. Inspected via this input sensitivity analysis, the biogas-linked agrosystem is regarded as F-sensitive.

Biogas energy efficiency (BEE) of BLAS is 0.20, implying that 0.20 biogas energy is produced by the system with respect to 1.00 energy input of the same quality, the BEE within the context of biogas subsystem is relatively high (2.71). With regard to emission mitigation intensity (EMI), planting is the biggest contributor (0.57 g/10^{10} sej)), followed by breeding, while biogas subsystem itself has the least mitigation effect.

3.2. Scenario analysis

According to the five policy scenarios (S1, S2, S3, S12 and S13) elucidated previously, we evaluate the future alternatives of BLAS (Table 6). The renewable resources, non-renewable resources and economic inputs of each system (subsystem) within different scenarios are altogether accounted and the relative emergy-based indices are comprehensively analyzed in contrast with the current status. Emergetic ternary diagrams of BLAS and its subsystems under these scenarios are also provided to demonstrate the holistic development trends and sustainability of BLAS and its subsystems, where the four analyses brought from EmTD technique are incorporated (Fig. 5).

4. Discussion

A huge economic development has taken place in BLAS since the introduction of biogas energy to the agriculture industry chain, which greatly improved the living standards of Yao minority in that region. As observed from the table, the empower density (6.37E+11 sej/m^2) and unit empower (5.78E+15 sej) in BLAS are higher than the average level of China [48] and Italy [49]. However, the problem of BLAS rests in the relatively high transformity (3.77E+05 sej/J) compared to other biogas systems (2.95E+04 sej/J in [28], 2.28E+05 sej/J in [29], and 5.32E+04 sej/J in [30]), which is also significantly higher than agricultural energy systems (such as [26,50–52]). The relatively high specific emergy of BLAS (1.53E+10 sej/g) and low environmental yield ratio (compared to the average level in Chinese agriculture) [48] reflect the same fact from biomass transformation and product output

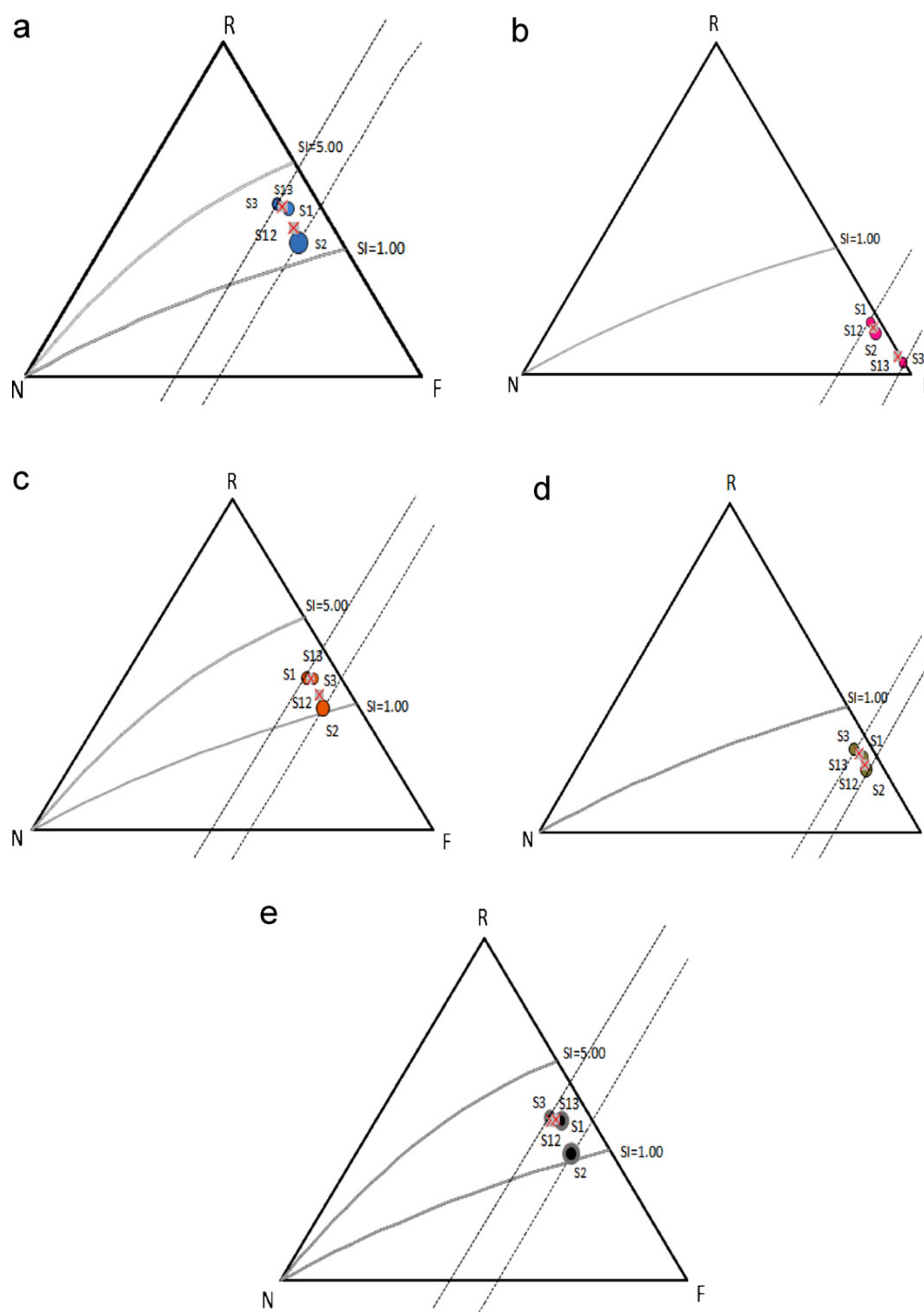


Fig. 5. Emergetic ternary diagrams of BLAS under five scenarios for (a) Planting subsystem, (b) Breeding subsystem, (c) Aquaculture system, (d) Biogas subsystem and (e) Overall BLAS. The size of system points are proportional to their total emergy input values. S1: Scenario I; S2: Scenario II; S3: Scenario II; S12: Scenario IV; S13: Scenario V. R: Renewable resources; N: non-renewable resources; F: economic inputs; SI: sustainability index.

Table 5
Emergy-based indices of BLAS and its subsystems (on per year basis).

	R (%)	N (%)	F (%)	BEE	EMI (g/10^{10} sej)	EYR	EIR	ELR	SI
BLAS	43	9	48	0.20	0.88	2.03	0.97	1.39	1.46
Planting	45	9	46	–	0.57	2.19	0.84	1.22	1.79
Breeding	42	8	51	–	0.21	1.22	4.63	5.69	0.21
Aquaculture	15	3	82	–	0.00	1.97	1.03	1.41	1.40
Biogas	22	4	74	2.71	0.10	1.35	2.87	3.60	0.37

Table 6
Aggregated emergy evaluation of BLAS under different scenarios (on per year basis).

		R (sej) (%)[a]	N (sej) (%)[a]	F (sej) (%)[a]	BEE[b]	EMI (g/10^{10}sej)	EYR	EIR	ELR	SI
S1	BLAS	5.73E+20 (47)	9.57E+19 (8)	5.61E+20 (46)	0.26	1.08	2.19	0.84	1.15	1.91
	Planting	5.26E+20 (50)	8.80E+19 (8)	4.31E+20 (41)	–	0.70	2.42	0.70	0.99	2.46
	Breeding	1.28E+19 (16)	1.93E+18 (2)	6.64E+19 (82)	–	0.26	1.22	4.51	5.34	0.23
	Aquaculture	2.78E+19 (46)	4.19E+18 (7)	2.90E+19 (48)	–	0.00	2.10	0.91	1.20	1.76
	Biogas	1.06E+19 (23)	1.61E+18 (3)	3.45E+19 (74)	4.24	0.12	1.36	2.81	3.39	0.40
S2	BLAS	5.73E+20 (37)	1.56E+20 (10)	8.14E+20 (53)	0.16	0.58	1.89	1.12	1.69	1.12
	Planting	5.26E+20 (40)	1.43E+20 (11)	6.42E+20 (49)	–	0.36	2.04	0.96	1.49	1.37
	Breeding	1.28E+19 (12)	3.14E+18 (3)	8.87E+19 (85)	–	0.13	1.18	5.57	7.18	0.16
	Aquaculture	2.78E+19 (37)	6.81E+18 (9)	4.09E+19 (54)	–	0.00	1.85	1.18	1.72	1.08
	Biogas	1.06E+19 (19)	2.62E+18 (5)	4.28E+19 (76)	3.11	0.09	1.31	3.22	4.26	0.31
S3	BLAS	5.73E+20 (48)	1.20E+20 (10)	5.08E+20 (42)	0.26	1.33	2.36	0.73	1.10	2.15
	Planting	5.26E+20 (51)	1.10E+20 (11)	3.86E+20 (38)	–	0.86	2.65	0.61	0.94	2.81
	Breeding	1.28E+19 (16)	2.42E+18 (3)	6.50E+19 (81)	–	0.30	1.04	25.38	30.36	0.03
	Aquaculture	2.78E+19 (46)	5.24E+18 (9)	2.75E+19 (45)	–	0.00	2.20	0.83	1.18	1.87
	Biogas	1.06E+19 (25)	2.01E+18 (5)	2.94E+19 (70)	4.52	0.11	1.43	2.32	2.95	0.49
S12	BLAS	5.73E+20 (41)	1.26E+20 (9)	6.88E+20 (50)	0.21	0.82	2.00	1.00	1.44	1.39
	Planting	5.26E+20 (45)	1.15E+20 (10)	5.37E+20 (46)	–	0.53	2.20	0.84	1.24	1.77
	Breeding	1.28E+19 (14)	2.54E+18 (3)	7.76E+19 (83)	–	0.20	1.20	5.06	6.26	0.19
	Aquaculture	2.78E+19 (41)	5.50E+18 (8)	3.49E+19 (51)	–	0.00	1.95	1.05	1.46	1.34
	Biogas	1.06E+19 (21)	2.12E+18 (4)	3.86E+19 (75)	3.79	0.11	1.33	3.03	3.83	0.35
S13	BLAS	5.73E+20 (47)	1.08E+20 (9)	5.35E+20 (44)	0.27	1.21	2.28	0.79	1.12	2.03
	Planting	5.26E+20 (51)	9.90E+19 (10)	4.09E+20 (40)	–	0.78	2.54	0.65	0.97	2.63
	Breeding	1.28E+19 (16)	2.18E+18 (3)	6.57E+19 (81)	–	0.28	1.13	14.94	17.85	0.13
	Aquaculture	2.78E+19 (46)	4.72E+18 (8)	2.83E+19 (47)	–	0.00	2.15	0.87	1.19	1.81
	Biogas	1.06E+19 (24)	1.81E+18 (4)	3.20E+19 (72)	4.57	0.12	1.39	2.57	3.17	0.44

[a] The numerical values (sej) and values in parentheses (%) indicate the value of R (or N, F) and its proportion of the total input.
[b] The values of BEE and EMI in scenario analysis are estimated based on the changes of system input (see Table 2), e.g., BEE = (BLAS,S1) = Y_b/F = (1.33E+20 sej × 110%)/5.61E+20 sej = 0.26, EMI (BLAS,S1) = EM/U = (1.41E+6 g + 4.93E+5 g) × (63 600 × 110%)/1.23E+21 sej = 1.08 g/10^{10} sej.

perspectives. This low energy transformation efficiency of the current system mainly results from the enormous economic investment from the government (especially in chemical fertilizers, and labor and services). In spite of this defect at the overall system scale, the biogas energy utilization of BLAS still proves its high efficiency considering the lowest energy transformity (9.16E+04 sej/J) of biogas component among all the subsystems and thus benefits the behavior of the overall system, whose value approximates other renewable energy carriers[3] [52–54]. Furthermore, the superiority of BLAS was also revealed by newly developed indices BEE and EMI. Evidently, the high biogas energy efficiency and significant emission mitigation effect exist in the current BLAS and is likely to remain so in future considering the continual biogas construction.

The results of emergy synthesis address another fact that is in contrast with the small proportion of renewable resources (R) and high economic input (F) in the system. This is further observed by using an EmTD again, which compares the resource input structure of BLAS with other systems (i.e., three small-scale biogas systems in [28–30] and the Chinese agricultural system in [23]) (Fig. 6) As shown, the percentage of local renewable resources in the total emergy inputs of BLAS (R% = 43%) is significantly different from other systems reported, i.e., lower than those of the small-scale biogas systems (from 79% to 66%) and higher than the Chinese agricultural system (23%). On the other side, the maintenance of BLAS is highly reliant on economic input (F) in that approximately half of the emergy is paid by human society (F% = 48%). As unveiled by the *F*-sensitivity line in Fig. 4b, this developmental trait is actually shared by all biogas-linked subsystems. It can be concluded that the incorporation of human labor-dependent agricultural subsystems is the main reason for a low R% (and a high F%) on the regional scale, where non-renewable purchases from human society become predominant. The overall BLAS, planting and aquaculture subsystem are within 1–5 sustainability zone in all scenarios, indicating the sustainable development is possible for them in the medium term, while breeding and biogas remain in an unsustainable situation constrained in 0–1 sustainability zone, which is due to the high environmental load carried by breeding and biogas subsystem (3 < ELR < 10). As illustrated by the comparative EmTD (Fig. 6), the sustainability index of the BLAS in Gongcheng (1 < SI < 5) is higher than the Chinese agricultural system (SI < 1) [23], whereas it is lower than the small-scale biogas systems (SI > 5) [28–30]. In view of the severe variation between two marginal F resource lines shown in EmTDs (Fig. 5), it is not difficult to see that the heavy proportion of economic input just mentioned also poses a big threat for system sustainable development. In terms of the

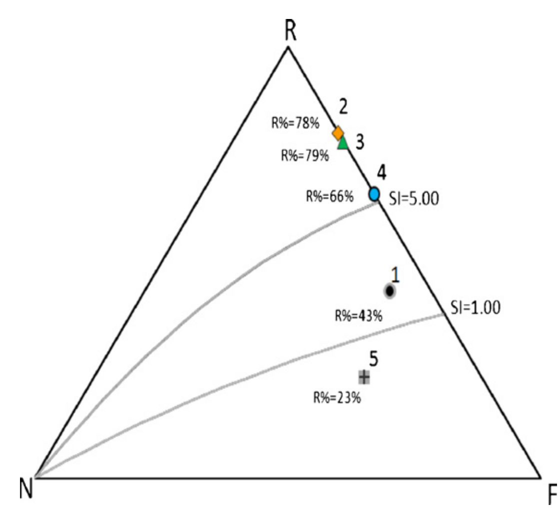


Fig. 6. Comparison of the resource input structures within different systems via EmDT. Point 1: BLAS; Point 2: a "Four-in-One" biogas-peach production system [28]; Point 3: a typical biogas project in Zhejiang (China) [29]; Point 4: a small-scale biogas-electricity generation system [30]; Point 5: Chinese agricultural system [23]. R: Renewable resources; N: non-renewable resources; F: economic inputs; SI: sustainability index; R%: the percentage of renewable resources.

[3] Note that the transformity of biogas chosen in this study is consistent with [28,29] based on the similar situation that biogas energy is processed and utilized on household basis in China, which is basically different from the production mode of [30].

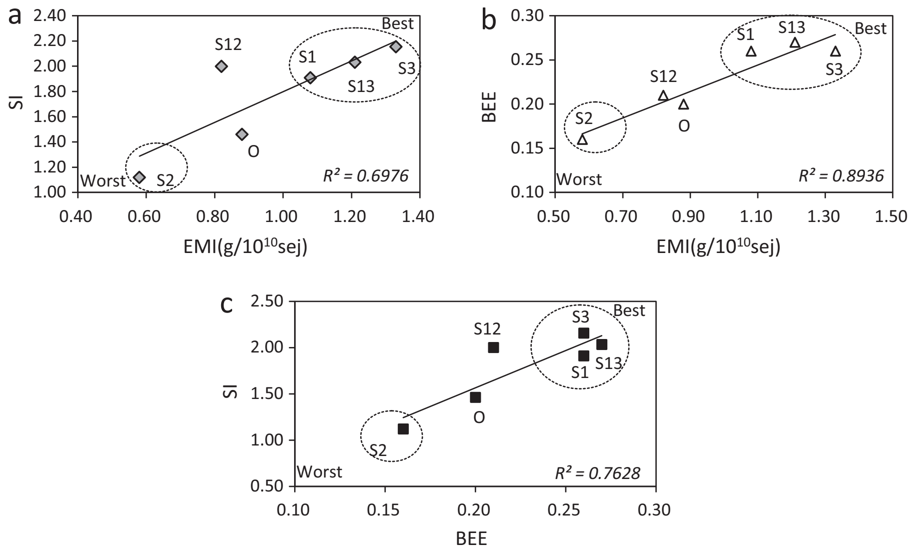


Fig. 7. Regression relations between EMI and SI (a), EMI and BEE (b) and BEE and SI (c) for current status (represented as "O") and five scenarios of BLAS. S1: Scenario I; S2: Scenario II; S3: Scenario II; S12: Scenario IV; S13: Scenario V. BEE: Biogas energy efficiency EMI: emission mitigation intensity; SI: sustainability index.

further development of BLAS, extra biogas constructions and effective technical renovation for biogas comprehensive utilization and cost reduction prove better alternatives over simple expansion of planting and breeding investment.

One of the most interesting findings is that the usually absolute conflict between emission mitigation and system growth regarding energy utilization is not found in BLAS. Instead, emissions mitigation, energy efficiency and sustainable development of overall biogas-linked agrosystem are discovered positively correlated, as shown in the regressions between each two of the three pertinent emergy-based indicators (EMI, SI and BEE), whose effect is most significant between emission mitigation intensity and biogas energy efficiency (Fig. 7). It is also clear that the subset constituted by S3, S13 and S1 served as the best-performance alternative for a better BLAS, while S2 remains to be the worst-performance option. The strategy of a transformation to more renewable and sustainable energy development is advocated by the Chinese government and will continue to be the focus of attention in the coming future. The renewable energy construction in the rural area is not only a response to this policy, but also an essential route to accomplish this aim. Household biogas plants have been developed in many rural counties in China, but the country still has a great potential in a more comprehensive and efficient utilization of biogas energy, especially in the improvement of traditional agrosystem. For this reason, it is crucial to identify a developmental pattern of biogas-linked agrosystem that fulfills the ultimate goals of being energy efficient, emission-free and sustainable in a long term simultaneously. The investigated BLAS of Gongcheng County is found to be a perfect demonstration of this possibility.

5. Conclusions

The first decade of the new century has passed, and China still faces the challenge of acquiring cleaner and safer energy sources beyond the country's economic expansion. There has been no clue that goes for a universal sustainable energy so far; in fact, modern evidences have shown the connection of renewable energy to the local agriculture and industry should be a preferred pattern in the pragmatic practice. The biogas-linked agrosystem in China investigated in this paper is an epitomized exploration for this. The economic and environmental performance of BLAS are analyzed and illustrated for the present as well as under future policy scenarios by combining the strengths of emergy synthesis and emergetic ternary diagrams. The combined methodology is legible and informative in presenting the alteration trends and relations of system (subsystem) performance that are difficult to track in conventional economic analysis. Moreover, the possibility of a tradeoff between high energy efficiency, significant emission mitigation and ideal system sustainability for biogas energy utilization is revealed. Although highly dependent on the external economic input at present stage, BLAS still serves as a promising option to sustain rural energy transition and energy safety of the country in face of the forthcoming energy scarcity.

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